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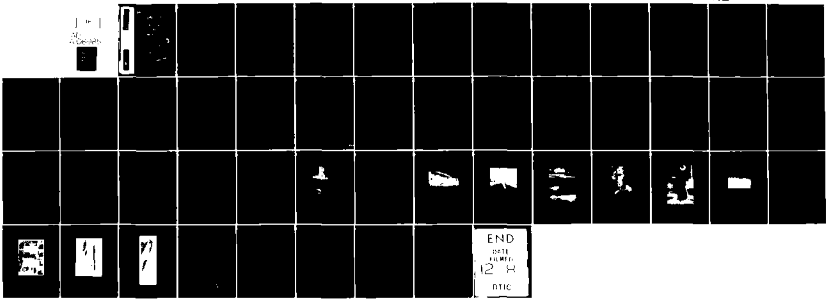

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LEVEL II

CUTTING ICE WITH "HIGH" PRESSURE WATER JETS

by

D.B. Coveney

Division of Mechanical Engineering

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CUTTING ICE WITH HIGH PRESSURE WATER JETS

DÉCOUPAGE DE LA GLACE PAR DE PUISSANTS JETS D'EAU

by/par

D.B. Coveney

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SUMMARY

The potential of "high" pressure water jets to cut slots in an ice sheet, primarily for possible use as an assist to ice breaking, has been under investigation by the Division of Mechanical Engineering of the National Research Council of Canada.

In the field, slots have been cut into and through fresh water ice, about 0.7 m thick with water jets applying up to about 260 kW of power to the ice. Each ice sheet consisted of a clear bottom layer and multiple upper layers of opaque white ice. The ice temperature just below the top surface ranged from −21°C to 0°C. In the laboratory, cuts to more than 17 cm were made in artificially grown, essentially clear, fresh water ice, and cuts to almost 25 cm were made in a simulated sea ice. Up to 50 kW was applied to the fresh water ice and up to 31 kW was applied to the simulated sea ice.

This report describes the ice cutting performance of small to moderate scale water jets. The majority of cuts produced a narrow, clean kerf, indicative of erosion in a ductile material, while other cuts produced a wide spalled trench, indicative of spalling in a brittle material. Still others produced a combination of the two modes of cutting, with a wide, shallow trench and a narrow, deep kerf below the trench. In many cases the ice was also crazed extensively by the water jet. The causes and the effects of these characteristics on ice cutting performance are discussed, along with the effects of jet traverse speed, nozzle diameter, nozzle pressure, nozzle stand-off, ice characteristics and the overall scale of the system. An empirical relationship, derived by regression analysis, is presented correlating the jet penetration to the power in the jet, the jet traverse speed, the nozzle stand-off and the estimated ice temperature.

(français au verso)

RÉSUMÉ

La possibilité de faire des coupures dans des plaques de glace à l'aide de puissants jets d'eau, principalement comme aide éventuelle pour briser la glace, a fait l'objet de recherches à la Division de Génie mécanique du Conseil national de recherches du Canada.

Lors d'essais effectués en milieu naturel, il a été possible de passer à travers de la glace d'eau douce ayant une épaisseur de 0,7 m à l'aide de jets d'eau exerçant une puissance de 260 kW sur la glace. Chaque plaque de glace se composait d'une couche inférieure transparente et de multiples couches supérieures blanches et opaques. La température de la glace juste en dessous de la surface supérieure se trouvait dans la gamme −21 à 0°C. En laboratoire, on a réalisé des découpes de plus de 17 cm dans la glace d'eau douce, transparente et artificielle, et des découpes de près de 25 cm dans de la glace marine simulée en appliquant respectivement jusqu'à 50 kW et 31 kW.

Dans le présent rapport on présente le rendement de jets d'eau à petite et moyenne échelle. La majorité des découpes faites étaient étroites et nettes, indiquant l'érosion d'une substance ductile, alors que d'autres étaient larges et irrégulières, témoignant de l'éclatement d'une substance cassante. D'autres encore combinaient les deux phénomènes: découpe large et peu profonde en surface prolongée d'une découpe étroite et profonde. Dans de nombreux cas aussi, le jet craquelait la glace sur une grande surface. On y étudie aussi les causes et les effets de ces caractéristiques sur le rendement du découpage ainsi que les effets de la vitesse d'avance du jet, du diamètre de l'ajutage, de la pression à l'ajutage, de l'éloignement de la lance, des caractéristiques de la glace et de l'échelle globale du système. Une analyse par régression a permis d'obtenir une relation empirique entre la pénétration du jet et la puissance de ce dernier, la vitesse d'avance, l'éloignement de la lance et la température estimée de la glace.

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CUTTING ICE WITH "HIGH" PRESSURE WATER JETS

1.0 INTRODUCTION

Cutting a slot into a sheet of ice can reduce its flexural strength considerably. Such a slot or multiple slots should be useful in easing the passage of an ice-breaking vessel through ice fields. The substantial weakening of an ice sheet by cutting one or more grooves in the ice by means of a high pressure water jet has been proposed as a possible means of extending current ice breaking capabilities and reducing fuel consumption. A relatively simple device, the high pressure water jet, used as a cutting tool, has the potential for development into a rugged, practical system for notching ice ahead of an ice-breaking vessel. Although mechanical modes of cutting can remove material more efficiently, a water jet has the advantage of non-mechanical contact and can cut with a substantial stand-off from the material being cut. This characteristic along with the ability to introduce a concentrated, high level of power into the material would provide significant practical advantages for the water jet cutting method when used to assist ice breaking.

Previous work by the Gas Dynamics Laboratory of the Division of Mechanical Engineering of the National Research Council of Canada in cutting a variety of materials with high pressure water jets and a few water jet cuts in ice at the University of Missouri at Rolla during frozen soil cutting trials for the U.S. Army Cold Regions Research and Engineering Laboratory led to exploratory small scale ice cutting trials in the Gas Dynamics Laboratory(1). While these initial trials showed that ice indeed could be cut with high pressure water jets, extrapolation of the results to a full scale system was impractical. After a subsequent series of field tests by CRREL at very high pressures(1), the Gas Dynamics Laboratory in collaboration with CRREL made various series of cuts in ice ranging from floating ice(2) to manufactured ice to lock wall ice collars with a pumping system about one full order of magnitude larger than the laboratory system. These cuts covered a fairly wide range of conditions, from relatively high speed shallow penetration cuts to low speed relatively deep penetration cuts. Extrapolating about two orders of magnitude from these results, while not at all reliable, did indicate that a realistic full scale system might be possible.

To further investigate the potential cutting ability of water jets in ice, larger scale field tests were initiated(3)(4)(7) by the Low Temperature Laboratory of the Division of Mechanical Engineering of the National Research Council of Canada and conducted in collaboration with the Gas Dynamics Laboratory. Through the course of this investigation, the field tests were supplemented by further fairly small scale laboratory tests(5)(6) including one series of cuts in a simulated sea ice(6).

2.0 ICE CUTTING SYSTEM

Cutting ice with a water jet is achieved by impacting a high velocity jet of water onto the ice. The resulting velocity and directional changes apply forces to the ice sufficient to fracture some of the weaker bonds between and within crystals. By traversing the jet across the surface of the ice a slot can be cut into or even through the ice. Figure 1 shows a water jet cutting such a slot in a floating ice sheet.

Typically, the jet is produced by accelerating high pressure water through a convergent steel nozzle. The high pressure water is supplied by a pumping system such as that shown in Figure 2, usually drawing the water for the jet from under the ice sheet. To produce a high quality coherent jet, the high pressure flow is stabilized in the cutting lance, either with a long straight pipe or with a flow stabilizer followed by a shorter straight pipe. Interchangeable nozzles terminate the cutting lance, with care taken to ensure that only minimal flow disturbances are introduced in the nozzle and its mounting. Control of the nozzle pressure is most often accomplished with a bypass returning some of the high pressure water back to the reservoir. For convenience and flexibility the various major components of the system are generally connected together with suitable hoses.

For most of our field testing (Fig. 3), the swing of a hydraulic crane with a telescoping boom was used to traverse the cutting lance, which was mounted in a lightweight triangular latticed column fitted to the head of the crane boom. Traverse speed was controlled by both the swing speed and the radius of the cutting arc. Nozzle stand-off could be adjusted by lifting or lowering the boom.

Suitable and accessible test sites were selected, on a spring-fed pond for the first series of field tests (March 1977)[3] and on the Ottawa River for the second and third series (February 1978[4] and February 1979[7] respectively). Both the crane and the high pressure pumps were positioned on solid ground as close to the ice as feasible (Fig. 3). For the field tests the ice thickness ranged up to about 0.75 metre.

In the laboratory, during one series of tests (July/August 1977) cuts were made in blocks of fresh water ice previously removed from ice sheets that had been grown in a large ice tank. In another series (July/August 1978)[5] cuts were made in fresh water ice sheets floating in the same ice tank and in a third series (January 1979)[6] cuts were made in a simulated sea ice sheet floating in another ice tank. The ice sheets were formed in insulated ice tanks, the fresh water ice by mechanical refrigeration in a cold chamber and the simulated sea ice by fan assisted natural freezing in an unheated building during winter. The fresh water ice ranged from about 10 cm to 30 cm thick while the simulated sea ice was almost 25 cm thick. After cutting out the blocks from the ice sheet, they were stored in a chest freezer held at the desired ice temperature until just before cutting.

The ice blocks were cut with water jets by linearly traversing the block of ice underneath a fixed cutting lance. For the ice sheets (Fig. 4), the lance was traversed linearly with a small carriage sliding on a beam. It was driven by an air cylinder for the cutting of fresh water ice and by a small electric drive for the cutting of simulated sea ice. This system was, in turn, mounted on a large carriage which could be moved perpendicularly to the traverse so that a series of cuts could be made.

3.0 TEST PROCEDURES

Fresh water ice was made in the laboratory cold chamber by cooling the water to near freezing and then lowering the chamber ambient temperature to -25°C. When a sufficient thickness of ice had formed, the chamber was stabilized overnight at the following day's required test temperature.

Simulated sea ice was made by adding commercial sea salt to fresh water until the salinity reached 16 ‰, cooling the resulting brine for one week until the brine was near freezing and then freezing for two weeks in early January 1979 at an average ambient temperature of about -14°C (range -26°C to $+4^\circ$C) until sufficient thickness of ice had formed.

Generally for all tests, prior to the ice cutting, measurements were made of ice thickness, ice temperature (3 to 4 cm below the ice surface) and ambient temperature. In most cases, the ambient temperature was also noted during the day while the ice cutting tests were taking place. In addition, samples were taken from each ice sheet for future determination of ice characteristics. For the simulated sea ice the brine salinity was monitored both at intervals during freezing and prior to the water jet cutting.

With the desired nozzle installed on the cutting lance and properly positioned for the start of a cut, the selected nozzle pressure was established and the initial nozzle stand-off was set. The jet (or the block) was then traversed at the desired speed, cutting a slot into or through the ice sheet. While cutting, the time to traverse a known distance was measured and recorded, and any significant features of the cutting were noted. After a suitable length of cut had been made, the traverse was stopped, the final nozzle stand-off was measured and the penetration was measured at intervals along the timed portion of the cut.

4.0 ICE CUTTING TESTS

In cutting the ice blocks, of a total of 103 tests, only 42 tests produced measurable cuts. Although a few tests had no measurable effect on the ice, most cracked or shattered the blocks so badly that the cuts could not be identified. In cutting the fresh water ice sheets, of a total of 162 tests, 2 were aborted, 5 were missing measurements of traverse speed and 3 were exploratory tests with a different type of nozzle. Thus, 194 cuts provided relevant data on water jet cutting of fresh water ice. In addition there was relevant data for 27 cuts in the simulated sea ice. The range of test conditions for both sets of data was as follows:

	Fresh Water Ice		Simulated Sea Ice	
	minimum	maximum	minimum	maximum
Traverse speed (km/h)	0.05	8.41	0.15	1.06
Hydraulic power (kW)	1.4	262	3.7	31
Nozzle diameter (mm)	1.02	16.66	1.51	
Nozzle pressure (MPa)	4.1	71	13	53
Nozzle flow (L/s)	0.16	26.2	0.29	0.59
Nozzle stand-off (cm)	3	152	7.5	
Penetration (cm)	0	74	2.8	24.8
Ambient temperature (°C)	-32	≈+ 25	-22	-15
Ice temperature (°C)	-21	0	-12	<- 1

All nozzles produced generally coherent jets (Figs. 1 & 4); however, some jets were better than others. Microscopic examination of the nozzles revealed some small flaws at the exit of some nozzles and in the smaller nozzles, some roughness in the bore and insufficient blending between the conical and cylindrical portions.

Uniformity of traverse speed during individual tests could not be maintained. The average variation for the 25 field tests for which more than one speed measurement was made was ±15% with the worst case ±40%. For the simulated sea ice cutting tests the traverse speed appeared somewhat more uniform than for the fresh water ice cutting tests. Also, when traversing with the hydraulic crane, the nozzle stand-off varied due to imperfect leveling of the crane.

In general, the water jet cuts varied from deep, narrow, clean kerf cuts (Fig. 5) to wide, spalled trenches blasted out of the ice (Fig. 6), while in some cases, a shallow spalled trench was produced with a deep kerf cut into the bottom of it. For the field tests, the cuts of the first series (Table I, Nos. 1-12) were all deep narrow kerfs about 5 cm wide with small particles of ice being removed from the slot with the spent water from the jet. However, for the second series (Table I, Nos. 55-95) a relatively clean cut kerf was obtained for most of the traverse in only two tests and for some of the traverse in three other tests. For all the other cuts of this series the ice tended to spall and break out in large chunks, somewhat smaller pieces and many small particles, leaving a trench of varying width up to 1 m wide but more usually 0.3 m to 0.5 m wide. The large chunks were often lifted out of the trench, while the smaller pieces were frequently thrown considerable distances; the small particles usually were ejected in the spray of spent water from the jet. Only for the shallowest cut of the third series (Table I, Nos. 135-194) was the ice removed primary by spalling. For all other cuts spalling was negligible. While some pieces of ice were broken out by the jet, presumably where a cut intersected an existing crack in the ice, most cuts resulted in a narrow fairly clean kerf about 13 mm wide similar to the cuts of the first series.

Of the measurable cuts in the ice blocks (Table I, Nos. 13-54) most produced a spalled groove, a few produced a recognizable kerf and the remainder simply melted a shallow groove in the ice. It was noticed that kerf cuts only occurred at the higher nozzle pressures (above 48 MPa) and at the higher ice temperatures (above -5°C), while spalling occurred between 7 and 52 MPa nozzle pressure and a melted groove was often found at nozzle pressures from 4 to 21 MPa.

Cuts in the laboratory fresh water ice sheets varied from deep, narrow, clean kerf cuts at the higher nozzle pressures to shallow, widely spalled cuts at the lower nozzle pressures. No sharply defined change in mode occurred; rather, there was a gradual increase in spalling as the pressure was lowered. Two other less apparent effects were also noticed; spalling tended to increase somewhat as traverse speed increased and it tended to decrease as each test series progressed. Also, as the jet was cutting relatively warm ice, much cracking of the ice sheet occurred, with some cracks running all the way to the side of the ice tank. For colder ice extensive crazing occurred, but only in the vicinity of the cut.

For the simulated sea ice most of the cuts were essentially clean kerf cuts with a small degree of surface spalling. However, for the first seven tests, as the pressure was reduced below about 40 MPa, the spalling became wider and deeper until, at about 13 MPa only a spalled trench was produced. Later in the day, cuts made with a pressure near 33 MPa were essentially clean with little or no spalling. No cracking or crazing of this ice sheet was observed.

Cuts through the fresh water ice tended to break large chunks of ice from the bottom of the ice sheets with the fracture planes running at angles between about 30° and 60° to the plane of the ice sheet. This was particularly noticeable on the samples cut out for determination of the ice characteristics (Fig. 7), and in the bottom profile of the ice at one side of a hole from which a pair of blocks was removed (Fig. 8). In this latter view, saw cuts were made to simulate the size and shape of the original water jet cut. Cuts through the simulated sea ice did not exhibit the angular break-out characteristic, however, in cutting out the simulated sea ice samples, the bottom couple of centimetres of ice broke roughly perpendicular to the plane of the ice sheet.

Also observed in cutting out the sample blocks in the field was that for the first series of tests the block could be cut easily with the water jet with no cracking or crazing of the ice; for the second series an attempt to cut a block with the water jet resulted in a shattered block; and for the third series a block was again easily cut out, but in this case there was extensive crazing, particularly of the clear ice.

5.0 ICE CHARACTERISTICS

All the sample blocks of ice cut during the field testing showed a layered structure (e.g. Fig. 7). The visually distinctive types of layers are noted in Figure 9 along with the thickness of these layers and the ice density at various locations through the thickness of the blocks. Both the white and semi-opaque layers themselves consisted of numerous individual but similar layers. While the clear ice from the first series appeared bubble free, both the second and third series samples contained some small bubbles.

To determine what effect the water jet cut may have had on individual ice crystals, a full depth slab was cut out of the sample block from the third series with a chain saw, leaving one water jet cut edge. This slab was subsequently processed into a partial set of individual thin sections (see Pounder[8]) with care taken to maintain the original position and orientation of each section. Photographs of each thin section were taken between crossed polaroids with a 1 cm reference grid and a set of prints was assembled into a montage to approximate a large area section of the ice (Fig. 10).

Examination of the thin sections showed no apparent localized shattering of ice crystals or any other localized effect peculiar to water jet cutting. However, the extensive crazing of the clear ice was seen to pass through several ice crystals with little or no deviation at crystal boundaries. The top opaque white ice consisted of snow ice with many layers of randomly oriented crystals up to about 5 mm in size — defined as Type T1 ice (see Michel and Ramseier[9]). The bottom clear ice consisted of columnar crystals mostly 1 to 3 cm thick with horizontal symmetry (horizontal orientation of the c-axis) — defined as Type S2 ice[9].

From the laboratory samples of fresh water ice, vertical thin sections, (e.g. Fig. 11 (1 cm reference grid)) showed that all three ice sheets consisted of bubble-free, columnar grained ice with horizontal symmetry — defined as Type S2 ice[9]. Although some crystals extended through the full thickness of the ice sheet, the size of the crystals varied considerably.

The samples cut from the simulated sea ice were rather fragile and could be easily crushed when first lifted out of the ice sheet. However, after a few minutes exposure to the cold ambient temperature they hardened and could be easily handled. Throughout most of their thickness they appeared to have a fine vertically elongated dendritic ice structure with voids or cavities between the dendrites.

The crystal structure of this simulated sea ice is shown in the vertical thin section of a sample taken from the centre of the ice sheet (Fig. 12 (1 cm reference grid)). The top layer consisted of large horizontal grains from 1 to 2 cm thick. Below this layer the crystals, still mostly 1 to 2 cm thick, became tilted more and more towards a vertical orientation until, by the bottom of the ice sheet, they were essentially vertical. Also visible in Figure 12 are the brine and air inclusions within the crystals. These inclusions, which appear as strings of tiny bubbles in the lower half of the figure, were expected to permit easier passage of the jet into the ice and consequently improved penetration relative to fresh water ice.

When it was assured that no further thin sections were needed, the remaining cores were melted down and the salinity of the resulting brine was measured. It was found to be 5.0 ‰. The salinity of the brine in the ice tank about 0.3 m below the ice was found to be 20.3 ‰ at the time the samples were cut from the ice sheet.

Although an attempt was made to characterize the strength of the various ice sheets with a simple field test, it was found to be unsatisfactory and no useful strength data was obtained.

6.0 ANALYSIS OF TEST DATA

For the cuts in fresh water ice and for those in simulated sea ice, separate relationships between the jet penetration and the jet parameters have been derived by multiple linear regression analyses.

From the general expression

$$Y = f(u, d, p, s) \tag{1}$$

where:

Y	=	average penetration (cm)
u	=	nozzle traverse speed (km/h)
d	=	nozzle diameter (mm)
p	=	nozzle pressure (MPa)
s	=	average nozzle stand-off distance (cm)

and assuming that a zero value for this function would result in a zero depth of cut, a first approximation was obtained by applying multiple linear regression analysis to a logarithmic transformation of this expression to yield ultimately an equation of the form:

$$Y = A \cdot u^B \cdot d^C \cdot p^D \cdot s^E \tag{2}$$

For the cutting of fresh water ice (Table I), analyses of this type were conducted both on individual series of tests and on combinations of data from groups of test series, including published and unpublished data from the early studies of NRC and USA CRREL[1][2](Table II). These analyses yielded exponents for nozzle traverse speed consistently near −0.5. Whenever the data covered a sufficient range of nozzle diameter and pressure, the exponent for nozzle diameter tended to range between about 1.5 and 2, while that for nozzle pressure tended to vary about 1.5. There was a general lack of useful correlation to nozzle stand-off.

It was recognized that the exponents for nozzle diameter and pressure were close to those that appear in the relationship describing the physical jet property of hydraulic power,

$$HP = C \cdot d^2 \cdot p^{3/2} \tag{3}$$

where:

- HP = hydraulic power (kW)
- C = dimensional constant
- d = nozzle diameter (mm)
- p = nozzle diameter (MPa)

With the simple relationship,

$$Y = f\left(\frac{HP}{\sqrt{u}}\right) \tag{4}$$

consistently good, highly significant correlations were obtained both for individual series of tests and for many of the combined data analyses. However, with the introduction of tests on ice at significantly lower temperatures there was a considerable reduction in the penetration of the jet. Consequently, from the measured ambient temperatures and the few related ice temperatures, an estimated ice temperature (near the surface) has been derived for each test of Tables I and II. Then by curve fitting an ice temperature factor to all the data combined, an improved overall relationship was obtained. In addition, it was found that reintroduction of nozzle stand-off now produced a significant correlation and further improved the overall relationship. The best overall relationship was

$$Y = 0.7 + 0.29\,\frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}} \tag{5}$$

with 95% confidence limits of

$$Y_{+2\sigma} = 2.3 + 0.30\,\frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}} \tag{6}$$

$$Y_{-2\sigma} = -1.0 + 0.27\,\frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}} \tag{7}$$

where: T_i = estimated ice temperature (°C)

Figure 13 shows a plot of the penetration "Y" versus the combined paremeter $\frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}}$ for all 249 cuts. The regression line (Eq. (5)) along with the $\pm 2\sigma$ limits is also shown in the same figure.

For a comparison of the effects of spalling versus those of kerfing, those tests that could be identified with either of the two modes were analyzed separately. In addition all cuts with 50% or more through penetration were eliminated from both sets of data. The resulting regressions were

for spalling:

$$Y = 3.3 + 0.19 \frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}} \tag{8}$$

for kerfing.

$$Y = 2.5 + 0.26 \frac{HP \cdot e^{T_i/20}}{\sqrt{u} \cdot s^{1/6}} \tag{9}$$

Equation (8) and the spalling cuts are shown in Figure 14, while Equation (9) and the kerfing cuts are shown in Figure 15.

In cutting the simulated sea ice (Table III), both nozzle diameter and stand-off were held constant throughout the full series of tests and ice temperature data was too limited to show an adequate relationship to penetration. The results of applying the same analysis procedure as used for the fresh water ice cutting suggested that the best relationship was

$$Y = 1.7 + 0.32 \frac{HP}{u^{3/4}} \tag{10}$$

However, for direct comparison with the fresh water ice cutting performance, a regression analysis based on $HP/\sqrt{u}$ also produced a highly significant equation with almost as good a fit to the data. With the introduction of a constant to account for stand-off (based on the effect found for fresh water ice cutting) the resulting equation provides a direct comparison to the cutting of 0°C fresh water ice (Eq. (5) where $e^{T_i/20} = 1$).

$$Y = -0.2 + 0.65 \frac{HP}{\sqrt{u} \cdot s^{1/6}} \tag{11}$$

with 95% confidence limits of

$$Y_{+2\sigma} = 3.4 + 0.80 \frac{HP}{\sqrt{u} \cdot s^{1/6}} \tag{12}$$

$$Y_{-2\sigma} = -3.7 + 0.50 \frac{HP}{\sqrt{u} \cdot s^{1/6}} \tag{13}$$

Figure 16 shows a plot "Y" versus the combined parameter $\frac{HP}{\sqrt{u} \cdot s^{1/6}}$ for all 27 cuts. The regression line of Equation (11) along with the $\pm 2\sigma$ limits is also shown in the same figure.

7.0 DISCUSSION

The fresh water ices cut in the field tests were generally a type of natural ice commonly found on lakes and rivers, having many layers of snow ice with an underlying layer of clear ice. Other than the candled top layers of the March 1977 ice, the principal difference was in the temperatures. For the first series in March 1977 the ice temperature was 0°C, while for the second series in February 1978 the ice near the top surface varied from about -11°C to -2°C and for the third series in February 1979 it ranged from about -18°C to -11°C. The colder ice was harder and stronger and obviously more difficult to cut. On the other hand the candled top layers of ice cut easily, resulting in over-estimation of the cutting ability of a water jet in more solid ice.

All the fresh water ice made in the laboratory was clear with the characteristics of ice grown unidirectionally from the free surface. The blocks of ice, having been stored in a chest freezer, were at a uniform temperature throughout varying from -18°C to 0°C. However, for the July/August 1978 tests, the three separate ice sheets, near their top surface, ranged from about -17°C to 0°C.

There was a variety of ices cut in the tests referred to in Table II, ranging from ice blocks to floating ice sheets to lock wall ice collars. However, all were apparently at or very near to 0°C and therefore relatively easy to cut.

The saline ice produced for these tests was a first approximation facsimile of first year sea ice. Its salinity at 5 ‰ was in the same range as the "typical average figure" of 4 ‰ cited by Pounder[8]. With its many inclusions and underlying fragile structure, this ice should have been more susceptible to water jet cutting than fresh water ice.

While the majority of cuts in both types of ice produced a narrow, clean kerf, indicative of erosion in a ductile material, others produced a wide spalled trench, indicative of spalling in a brittle material. In some cases both modes of cutting occurred simultaneously with a kerf below a trench. Although there was no clear demarcation between kerfing and spalling, the results of this test program suggest that about 40 MPa was needed to cut a kerf without excessive spalling in either fresh water ice or in the simulated sea ice. Still higher pressures generally produced cleaner cuts. For equivalent conditions a spalled cut tended to be shallower than a kerf cut, although not as much as originally expected. A few small scale cuts simply melted a groove in the ice.

For the first few simulated sea ice tests, when the ice was still cold, cutting through the hard surface layer, in all cases, resulted in some degree of surface spalling, becoming more pronounced as the nozzle pressure was reduced until, at 13 MPa, only spalling occurred. Later in the day, when the ice was presumably warmer due to the flooding of the surface during each test, the degree of spalling became negligible (down to a nozzle pressure of 33 MPa). Cutting into or through the underlying softer ice produced clean kerf cuts.

Extensive cracking and crazing of the ice sheets did not appear to affect subsequent cuts, with the exception that a sizeable piece of ice would occasionally be broken out as the jet passed over or near a crack. While extensive crazing of the clear ice has been observed throughout some of the ice blocks cut out by the water jet for ice samples, there was no indication that there was any weakness at these locations. Even in making the thin sections, no fractures occurred.

In the absence of suitable ice strength data, an empirical ice temperature factor ($e^{T_i/20}$) has been included in the analyses to provide a first approximation to the effects of variable ice strength. The regression analyses have confirmed that ice temperature has a considerable effect on the cutting ability of a water jet in fresh water ice. However, ice temperature will be governed, not just by ambient temperature, but also by flooding of the ice surface during the cutting tests, especially in the laboratory ice tanks. Consequently, the ice was subjected to short periods of warming from the flooding, followed by longer periods of cooling from the air. Because of the relatively high thermal inertia of the ice, it is expected that the heat supplied by the flooding produced only a gradual overall warming of the ice above its initial temperature which started in equilibrium with the ambient temperature.

Cuts penetrating through the full thickness of the ice may not truly represent the jet's cutting ability *in* ice. Apparently, final full penetration occurs by the fracture of sizeable pieces of ice from the bottom of the ice sheet. While the kerf portion of the cut is characterized by localized overstressing of the ice by direct *pressure* from the jet, with small particles being broken off and washed away, the chunks of ice broken from the bottom of the ice sheet suggest that a point is reached where the ice remaining below the kerf is incapable of supporting the impinging *force* of the water jet. Thus through cuts are produced by a combination of two different modes of ice failure. However, the *cutting ability of a jet in ice is determined only by the kerf cutting ability of the jet.* As can be seen for example in Figure 16, there can be either excess power in the jet that could cut still deeper if the ice were thicker, or insufficient power to cut through even the tested thickness without the breaking away of chunks from the bottom of the ice sheet. Since through cuts can either underestimate a jet's cutting ability or overestimate it, and since such cuts, being the deepest achieved in any particular test series, can have an inordinate effect in determining the slope of a regression line, care should be taken to avoid excessive reliance on through cuts for extrapolation of test data to cuts in thicker ice.

For the fresh water ice cutting regression analysis, Equation (5) provides a statistically excellent fit to the entire body of data from both Tables I and II. Nevertheless, some of the data points remain a considerable distance from the regression line, especially those points representing the deeper cuts. When the data was separated into groups known to be either cutting or spalling and the through cuts were eliminated, the scatter of the points was reduced. As suspected, the results of this separation indicate that spalling does produce considerably less penetration than does kerfing.

$$Y_{spalling} \approx 0.73\, Y_{kerfing}$$

Note that even though spalling may produce a shallower cut it still may be more desirable for some applications.

In addition it is to be noted that Equation (9) for kerfing only indicated a slightly lower penetration than Equation (5) for all cuts. This is likely due in large part to the elimination of the "through" cuts, and to some extent, to the elimination of some of the unknown-mode cuts from Table II.

For the simulated sea ice, the effect of traverse speed, as indicated by its exponent of -3/4, may be greater (Eq. (10)) than that for fresh water ice (Eq. (5)) where the exponent is -1/2. However, with only 27 data points and with a correlation almost as good with -1/2 exponent (Eq. (11)), there is insufficient data to establish more firmly the effect of traverse speed. Nevertheless, a comparison of the slope of Equation (11) to that of Equation (5) indicates that penetration in the simulated sea ice was more than double that in fresh water ice when the jet parameters were similar. Apparently, the brine and air inclusions within the saline ice structure did permit easier jet penetration into this ice, as expected.

8.0 CONCLUSIONS

Most of the fresh water ices cut with water jets have been of good quality, varying from clear, bubble-free ice to snow ice. However, they have varied considerably in temperature with a consequent variation in hardness and strength.

The saline ice made for these tests was a reasonable laboratory simulation of first year sea ice, but on a reduced scale.

A large number of cuts have now been made in fresh water ice with small to moderate scale water jets, a few have also been made in a simulated sea ice with small scale water jets. In the majority of cases a narrow, clean kerf was cut in both types of ice. However, below about 40 MPa nozzle pressure the cut consisted mostly of a wide spalled trench. The kerf was apparently produced by erosion in a ductile material while the spalled trench was apparently produced by brittle fracture. For those cuts in fresh water ice that could be identified as either kerfing or spalling the penetration by spalling was only about three-quarters as deep as that by kerfing.

Apparently, extensive cracking and crazing of the ice sheets did not significantly weaken them.

As the fresh water ice temperature dropped substantially below freezing, a considerable reduction in penetration capability occurred. This was apparently due to an increase in ice strength. A first approximation of this effect was obtained by applying an empirical correction factor to the penetration -- jet parameters relationship based on the estimated temperature of the ice near the surface. This factor enabled the data from the entire range of temperatures to be explained by a single highly significant regression equation. Insufficient data was available to establish a similar factor for the simulated sea ice.

Cuts penetrating through the full thickness of an ice sheet may not truly represent the cutting ability of a water jet *in* ice. A jet that penetrates an ice sheet with surplus power may cut even deeper in a thicker ice sheet, but one that penetrates with marginal power may not cut as deep in a thicker ice sheet.

With all the fresh water ice cutting data of Tables I and II taken together, Equation (5) represents a statistically excellent fit to the data. It confirms that the jet parameters, hydraulic power and the square root of traverse speed, are the important factors and that ice strength can be taken into account by a simple empirical ice temperature factor ($e^{T_I/20}$). Use of this entire body of data has also revealed that nozzle stand-off does have a significant effect, albeit a small one.

While Equation (5) indicates a linear relationship between jet penetration and the jet parameters over the range covered, there is no evidence to suggest that it will not level off at some point beyond the present range. Nevertheless, it is interesting to speculate what extrapolation to a larger system might produce. For example, 4000 kW of power input into the ice at a traverse speed of 5.5 km/h might cut upward of 3 m of fresh water ice at 0°C and about 1.5 m at -20°C.

For the simulated sea ice the regression analyses indicate that the effect of traverse speed on the jet penetration is not clearly defined. Although the same general function fitted to the cutting of fresh water ice, $Y = f(HP/\sqrt{u})$, also fits the cutting of the saline ice very well, the general function $Y = f(HP/u^{0.75})$ provides a marginally better fit. With such an uncertainty, no attempt at extrapolation to higher power levels can be justified.

At the rather small scale of these tests the jet penetration into the simulated sea ice was greater than into fresh water ice, all other conditions being equivalent. While the cutting of saline ice on a larger scale shows promise of even deeper cuts relative to cuts in fresh water ice, tests on the larger scale will be necessary to confirm this.

9.0 ACKNOWLEDGMENTS

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TABLE I

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
March 1977 — Cuts made in floating pond ice (Ref. 3)										
1	50.8	0.67	9.52	11	10.7	121	30	+10	0	
2	55.9	0.26	9.52	13	11.6	152	33	+10	0	
3	50.8	0.19	9.52	13	11.3	142	17	+10	0	part "through"
4	50.8	0.24	9.52	13	11.3	142	91	+16	0	part "through"
5	71.1	0.21	12.70	11	18.6	200	152	+16	0	100% "through"
6	71.1	0.23	12.70	10	18.2	187	30	+16	0	100% "through"
7	71.1	0.20	12.70	11	18.5	198	99	+16	0	100% "through"
8	71.1	0.70	12.70	11	18.4	194	152	+16	0	100% "through"
9	55.9	0.79	12.70	11	18.4	194	127	+16	0	
10	53.3	0.33	12.70	11	18.4	194	122	+16	0	
11	71.1	0.32	16.66	7.2	26.2	190	122	+16	0	100% "through"
12	25.4	1.99	16.66	7.2	26.2	190	122	+16	0	
July-August 1977 — Cuts made in ice blocks from floating ice sheets										
13	5.1	0.64	1.02	48	0.25	12	5	≈ +20 to +25	0	
14	0.5	5.71	1.02	34	0.21	7.3	5		0	spalling
15	2.0	5.71	1.02	48	0.25	12	5		0	spalling
16	2.5	5.71	1.02	69	0.30	21	5		0	
17	1.4	5.71	1.02	21	0.16	3.4	5		- 5	spalling
18	1.4	5.71	1.02	34	0.21	7.3	5		- 5	spalling
19	1.5	5.71	1.02	34	0.21	7.3	5		- 5	spalling
20	1.9	8.41	1.02	48	0.25	12	5		- 5	

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
July-August 1977 — Cuts made in ice blocks from floating ice sheets (Cont'd)										
21	1.5	8.41	1.02	48	0.25	12	5		- 5	
22	4.6	0.64	1.60	52	0.65	34	8		0	
23	7.6	0.64	1.60	69	0.75	52	8		0	
24	4.1	5.71	1.60	48	0.62	30	8		0	spalling
25	5.1	5.71	1.60	69	0.75	52	8		0	
26	1.3	0.27	1.60	21	0.41	8.5	8		- 5	spalling
27	1.0	0.37	1.60	21	0.41	8.5	8		- 5	melted groove
28	0.4	0.64	1.60	10	0.28	2.7	8		- 5	melted groove
29	0.4	0.64	1.60	14	0.33	4.6	8		- 5	melted groove
30	1.3	8.38	1.60	21	0.41	8.5	8	≈	- 5	spalling
31	1.1	8.38	1.60	21	0.41	8.5	8	+20 to +25	- 5	spalling
32	1.9	8.38	1.60	21	0.41	8.5	5		- 5	spalling
33	1.9	8.38	1.60	34	0.53	18	10		- 5	spalling
34	1.9	8.38	1.60	34	0.53	18	10		- 5	spalling
35	3.0	8.38	1.60	48	0.62	30	9		- 5	spalling
36	0.8	0.27	1.60	10	0.28	2.7	8		-18	melted groove
37	1.3	0.27	1.60	21	0.41	8.5	8		-18	melted groove
38	1.5	0.27	1.60	28	0.47	13	8		-18	spalling
39	1.5	0.27	1.60	34	0.53	18	8		-18	spalling
40	0.8	0.64	1.60	34	0.53	18	8		-18	spalling
41	0.8	0.27	2.18	4.1	0.34	1.4	11		0	melted groove
42	1.1	0.27	2.18	6.9	0.44	3.0	11		0	spalling
43	0.5	0.37	2.18	4.1	0.34	1.4	11		0	melted groove

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
July-August 1977 — Cuts made in ice blocks from floating ice sheets (Cont'd)										
44	0.3	0.64	2.18	4.1	0.34	1.4	11		0	melted groove
45	0.3	0.64	2.18	4.1	0.34	1.4	11		0	melted groove
46	1.5	0.64	2.18	6.9	0.44	3.0	11		0	spalling
47	3.3	0.64	2.18	10	0.54	5.6	11		0	spalling
48	1.0	6.31	2.18	21	0.76	16	11	≈	- 5	spalling
49	0.9	0.27	2.57	4.1	0.47	1.9	13	+20 to +25	0	spalling
50	0.3	0.64	2.57	4.1	0.47	1.9	13		0	melted groove
51	0.4	0.64	2.57	6.9	0.61	4.1	13		0	spalling
52	0.5	0.64	2.57	10	0.74	7.7	13		0	spalling
53	1.3	0.27	3.45	4.8	0.92	4.4	11		0	melted groove
54	0.5	0.64	3.45	4.8	0.92	4.4	11		0	melted groove
February 1978 — Cuts made in floating river ice (Ref. 4)										
55	8.7	2.74	9.60	14	12.3	177	30	-13	-11	spalling
56	8.7	1.63	11.13	13	15.9	214	30	- 8	- 6	spalling
57	8.5	2.54	14.27	10	22.9	235	30	- 8	- 5	spalling
58	5.0	1.46	12.75	12	19.8	238	30	-13	- 9	spalling
59	10.6	1.44	9.60	14	12.2	173	30	-12	- 8	spalling
60	11.8	2.47	9.60	14	12.1	171	30	-12	- 5	spalling
61	17.0	1.32	9.60	14	12.2	173	91	- 7	- 4	spalling
62	19.7	1.23	11.13	14	16.1	221	91	- 7	- 4	spalling
63	17.7	1.41	12.75	12	19.9	240	91	- 6	- 2	spalling

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
February 1978 — Cuts made in floating river ice (Ref. 4) (Cont'd)										
64	12.1	1.65	14.27	11	23.3	247	91	- 6	- 2	spalling
65	20.4	1.50	9.60	14	12.2	173	91	- 5	- 3	spalling
66	20.0	1.44	11.13	14	16.0	219	91	- 5	- 3	spalling
67	16.6	1.26	9.60	14	12.2	173	91	- 8	- 6	spalling
68	18.0	1.23	11.13	14	16.0	217	91	- 7	- 6	spalling
69	43.7	0.42	9.60	14	12.2	173	60	-11	- 6	spalling & 35% "through"
70	56.1	0.35	9.60	14	12.2	175	104	-10	- 7	spalling & 55% "through"
71	41.4	0.35	11.13	14	16.0	217	61	-10	- 5	spalling & 35% "through"
72	52.3	0.31	11.13	14	16.0	217	97	- 9	- 6	spalling & 65% "through"
73	27.2	0.24	12.75	12	19.7	235	80	-12	- 9	spalling
74	37.3	0.27	14.27	10	23.1	239	76	-11	- 8	spalling & 30% "through"
75	38.9	0.27	12.75	12	19.8	236	100	-10	- 7	spalling & 35% "through"
76	29.0	0.55	9.60	14	12.3	176	80	- 9	- 7	spalling
77	30.0	0.55	11.13	14	16.0	217	91	- 8	- 6	spalling
78	25.1	0.91	11.13	14	16.0	219	91	- 7	- 5	spalling
79	24.4	0.73	9.60	14	12.1	175	52	- 7	- 5	spalling
80	46.0	0.18	9.60	14	12.3	176	41	-15	- 6	
81	37.1	0.15	9.60	13	11.5	146	39	-14	- 8	spalling
82	33.3	0.27	9.60	11	10.7	116	28	-13	- 4	spalling
83	34.5	0.15	9.60	11	10.7	116	56	-12	- 6	spalling
84	25.9	0.53	9.60	13	11.5	144	70	-10	- 5	spalling
85	35.1	0.15	11.13	12	15.0	178	37	- 9	- 4	spalling
86	31.5	0.17	11.13	10	14.0	145	43	- 8	- 6	spalling

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
February 1978 — Cuts made in floating river ice (Ref. 4) (Cont'd)										
87	58.4	0.23	11.13	14	16.0	217	24	- 8	- 2	80% "through"
88	38.1	0.26	11.13	12	15.1	181	61	- 7	- 2	spalling
89	24.9	0.46	11.13	10	14.0	145	65	- 7	- 2	spalling
90	33.5	0.22	11.13	14	16.0	219	37	- 8	- 7	spalling
91	22.9	0.30	12.75	10	17.8	172	33	- 8	- 5	spalling
92	49.8	0.27	12.75	12	19.8	236	58	- 7	- 5	spalling & 50% "through"
93	26.4	0.32	12.75	10	17.8	174	63	- 7	- 5	spalling
94	26.9	0.19	14.27	10	23.1	242	23	- 7	- 4	spalling
95	36.6	0.34	14.27	11	23.2	244	66	- 7	- 3	spalling
July-August 1978 — Cuts made in floating ice sheet (Ref. 5)										
96	6.6	1.43	1.51	53	0.58	31	3	- 6	- 4	
97	6.4	1.74	1.51	47	0.55	26	3	- 4	- 2	
98	5.3	1.70	1.51	40	0.51	20	3	- 6	- 2	
99	3.8	1.87	1.51	33	0.46	15	3	- 4	- 1	spalling
100	3.3	2.08	1.51	27	0.42	11	3	- 5	- 1	spalling
101	7.1	1.21	1.51	47	0.55	26	3	- 5	0	
102	7.1	1.01	1.51	40	0.51	20	3	- 5	0	
103	6.1	1.15	1.51	33	0.46	15	3	- 6	- 1	
104	4.8	1.24	1.51	27	0.42	11	3	- 4	- 2	spalling
105	8.9	1.30	1.51	53	0.58	31	3	- 5	- 3	4 mm kerf
106	10.4	0.69	1.51	53	0.58	31	3	- 5	- 2	77% "through"

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
July-August 1978 — Cuts made in floating ice sheet (Ref. 5) (Cont'd)										
107	9.1	0.68	1.51	47	0.55	26	3	- 4	- 1	4 mm kerf
108	11.2	0.68	1.51	53	0.58	31	3	- 4	- 1	
109	6.4	1.92	1.51	53	0.58	31	3	- 4	0	
110	8.6	1.37	1.51	53	0.58	31	3	- 4	0	
111	7.4	1.26	1.51	53	0.58	31	3	- 2	0	
112	5.3	1.68	1.51	53	0.58	31	3	-10	- 6	
113	6.1	1.66	1.51	47	0.55	26	3	-10	- 6	
114	4.3	1.98	1.51	40	0.51	20	3	-10	- 5	
115	6.9	1.28	1.51	53	0.58	31	3	-10	- 4	
116	13.2	0.18	1.51	53	0.58	31	3	-10	- 3	96% "through"
117	6.1	1.76	1.51	53	0.58	31	3	- 9	- 2	
118	11.2	0.68	1.51	53	0.58	31	3	- 9	- 1	69% "through"
119	6.4	2.05	1.51	57	0.61	35	3	-10	- 6	
120	8.4	1.41	1.51	59	0.61	36	3	-10	- 6	
121	8.9	1.12	1.51	59	0.61	36	3	- 9	- 5	
122	11.4	0.75	1.51	59	0.62	37	3	-10	- 4	54% "through"
123	17.3	0.16	1.51	59	0.61	36	3	-10	- 3	94% "through"
124	14.0	0.46	1.51	59	0.61	36	3	-10	- 2	46% "through"
125	2.8	1.61	1.40	66	0.56	37	3	-29	-17	
126	6.4	0.27	1.40	66	0.56	37	3	-32	-17	
127	6.1	0.22	1.40	66	0.56	37	4	-32	-16	
128	13.0	0.11	1.40	66	0.56	37	3	-31	-14	62% "through"
129	11.7	0.24	1.40	68	0.56	38	3	-29	-12	3 mm kerf

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
July-August 1978 — Cuts made in floating ice sheet (Ref. 5) (Cont'd)										
130	4.8	0.38	1.40	68	0.56	38	3	-25	-13	
131	6.4	0.27	1.40	68	0.56	38	3	-29	-15	
132	9.1	0.18	1.40	68	0.56	38	3	-30	-14	
133	14.5	0.05	1.40	68	0.56	38	3	-30	-13	
134	13.0	0.29	1.40	68	0.56	38	3	-30	-12	
February 1979 — Cuts made in floating river ice (Ref. 7)										
135	21.6	0.25	2.87	57	2.18	123	32	-18	-13	
136	43.9	0.42	2.87	71	2.44	173	20	-18	-13	9 mm kerf
137	17.8	0.67	2.87	71	2.44	173	11	-18	-13	
138	11.9	2.43	2.87	71	2.44	173	13	-17	-13	
139	24.1	0.25	2.87	62	2.28	142	5	-17	-13	
140	50.5	0.14	3.56	70	3.72	262	16	-24	-18	
141	30.5	0.44	3.56	66	3.61	239	20	-23	-18	
142	31.8	0.40	3.56	66	3.61	239	13	-23	-18	
143	25.4	0.68	3.56	66	3.61	239	5	-23	-18	
144	22.4	1.15	3.56	66	3.61	239	4	-22	-17	
145	19.6	0.65	3.56	63	3.52	221	19	-22	-17	
146	20.6	1.39	3.56	64	3.56	228	20	-22	-17	
147	41.1	0.18	3.56	64	3.56	228	13	-22	-17	
148	23.9	0.62	3.56	64	3.56	228	16	-22	-17	
149	31.0	0.40	3.56	64	3.56	228	11	-22	-17	

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
February 1979— Cuts made in *floating* river ice (Ref. 7) (Cont'd)										
150	16.8	0.99	3.56	57	3.34	189	14	-22	-17	
151	40.9	0.14	3.56	57	3.34	189	17	-21	-17	
152	24.9	0.45	3.56	52	3.22	169	17	-21	-17	
153	11.4	2.23	3.56	55	3.30	182	20	-21	-17	
154	19.6	0.43	3.56	54	3.26	175	17	-21	-17	
155	22.4	0.25	3.56	46	3.02	140	18	-20	-17	
156	7.9	2.53	3.56	45	2.97	133	14	-20	-16	
157	18.8	0.39	3.56	44	2.95	130	9	-19	-16	
158	13.7	1.02	3.56	43	2.93	127	17	-19	-16	
159	4.8	3.87	3.56	35	2.63	93	13	-19	-16	spalling
160	15.0	0.20	3.56	34	2.58	87	17	-19	-16	
161	11.2	0.71	3.56	33	2.56	85	14	-19	-16	
162	11.4	0.47	3.56	34	2.58	87	15	-18	-16	
163	16.3	1.83	3.56	68	3.65	247	11	-18	-16	
164	41.9	0.20	3.56	68	3.65	247	23	-18	-16	
165	21.3	0.95	3.56	67	3.63	243	27	-19	-16	13 mm kerf
166	27.4	0.39	3.56	67	3.63	243	29	-19	-16	
167	9.9	3.37	4.09	48	4.08	197	18	-20	-14	
168	29.0	0.27	4.09	48	4.08	197	17	-20	-14	13 to 19 mm kerf
169	23.1	0.53	4.09	48	4.08	197	15	-19	-14	
170	20.1	1.20	4.09	48	4.08	197	19	-19	-14	
171	25.1	0.66	4.09	48	4.08	197	12	-19	-14	
172	13.2	1.40	4.09	41	3.75	152	14	-18	-14	9 to 13 mm kerf

TABLE I (Cont'd)

CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
February 1979 — *Cuts made in floating river ice (Ref. 7) (Cont'd)*										
173	6.9	5.30	4.09	41	3.78	156	19	-18	-13	
174	24.4	0.25	4.09	40	3.71	149	15	-17	-13	9 to 13 mm kerf
175	18.3	0.76	4.09	40	3.71	149	17	-17	-12	
176	22.9	0.51	4.09	40	3.71	149	11	-17	-12	
177	12.2	1.30	4.09	33	3.38	112	18	-17	-12	
178	19.0	0.28	4.09	33	3.38	112	28	-17	-13	
179	8.1	5.11	4.09	32	3.34	108	18	-17	-13	
180	20.8	0.31	4.09	32	3.34	108	20	-17	-12	
181	13.0	1.09	4.09	32	3.34	108	15	-16	-12	
182	33.5	0.19	4.09	48	4.05	193	39	-16	-12	
183	39.1	0.11	4.09	48	4.05	193	53	-17	-13	
184	30.7	0.28	4.09	48	4.05	193	56	-16	-13	
185	26.7	0.33	4.09	48	4.05	193	52	-16	-13	
186	24.1	0.26	4.57	34	4.31	149	15	-16	-12	
187	28.4	0.22	4.57	34	4.27	144	27	-15	-12	13 mm kerf
188	25.9	0.29	4.57	34	4.27	144	5	-15	-12	
189	16.3	1.28	4.57	34	4.27	144	3	-15	-11	
190	37.6	0.25	3.56	63	3.54	225	11	-15	-11	
191	62.0	0.16	3.56	67	3.63	243	23	-15	-11	64% "through"
192	41.7	0.22	3.56	68	3.67	251	14	-15	-11	
193	45.5	0.21	3.56	68	3.65	247	14	-15	-11	
194	44.2	0.15	3.56	65	3.58	232	19	-17	-13	

TABLE II

EARLY TESTS CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
1971										
1	0.4	0.55	0.58	17	0.050	0.86	6		0	
2	0.8	0.55	0.58	34	0.070	2.4	6		0	(Ref. 1)
3	2.6	0.55	0.58	69	0.10	6.9	6		0	
1972										
4	3.8	0.62	0.20	310	0.026	7.9	1	≈+20	0	
5	3.0	0.64	0.20	205	0.022	4.3	1		0	
6	1.1	0.63	0.20	108	0.015	1.6	1		0	Cuts made in ice blocks
7	12.7	0.05	0.20	105	0.015	1.6	1		0	(Ref. 1)
8	18.3	0.05	0.20	208	0.021	4.3	1		0	
9	11.7	0.21	0.20	310	0.026	7.9	1		0	
10	8.1	0.21	0.20	206	0.021	4.3	1		0	
11	2.2	0.21	0.20	104	0.015	1.5	1		0	
1973										
12	16.5	1.26	0.51	689	0.24	164	3	≈ 0	0	
13	17.8	1.82	0.51	689	0.24	164	3		0	Cuts made in floating ice
14	12.7	5.54	0.51	689	0.24	164	3		0	sheet (Ref. 1)
15	5.1	5.12	0.51	345	0.17	58	3		0	
16	9.7	4.57	0.51	689	0.24	164	3		0	

TABLE II (Cont'd)

EARLY TESTS CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
1973 (Cont'd)										
17	15.2	6.53	0.51	689	0.24	164	3		0	
18	7.1	3.46	0.30	414	0.066	27	2		0	
19	7.6	1.52	0.30	414	0.066	27	2		0	Cuts made in ice blocks
20	11.4	1.08	0.30	414	0.066	27	2		0	from floating ice sheet
21	12.7	1.68	0.41	414	0.12	49	3		0	(Ref. 1)
22	16.5	1.27	0.41	414	0.12	49	3		0	
23	16.5	1.21	0.41	414	0.12	49	3		0	
February 1974										
24	5.6	5.85	2.26	64	1.44	92	8	0^+	0	
25	6.6	4.43	2.26	66	1.45	95	8	0^+	0	
26	8.1	2.91	2.26	65	1.45	95	8	0^+	0	
27	8.4	2.71	2.26	67	1.47	98	8	0^+	0	Cuts made in floating ice
28	15.0	1.06	2.26	68	1.48	100	8	0^+	0	sheet (Ref. 2)
29	20.3	0.73	2.26	68	1.48	100	8	0^+	0	
30	21.6	0.59	2.26	69	1.49	103	8	0^+	0	
31	22.1	0.25	1.60	76	0.78	59	8	0^+	0	
32	15.0	0.62	1.60	81	0.81	65	8	0^+	0	
December 1974										
33	30.5	0.22	2.18	59	1.28	75	13	0^+	0	Cuts made in manufactured
34	61.0	0.05	2.18	63	1.33	83	13	0^+	0	ice blocks

TABLE II (Cont'd)

EARLY TESTS CUTTING FRESH WATER ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Estimated Ice Temperature (near surface) T_i(°C)	Remarks
December 1974 (Cont'd)										
35	92.7	0.05	2.18	65	1.35	87	5	0^+	0	
36	30.5	0.05	3.86	21	2.38	49	5	0^+	0	
37	66.0	0.05	1.60	83	0.82	68	8	0^+	0	
38	106.7	0.05	2.18	69	1.39	96	5	0^+	0	Cuts made in manufactured ice blocks
39	73.7	0.05	2.18	65	1.35	87	10	0^+	0	
40	34.3	0.16	2.18	66	1.36	90	10	0^+	0	
41	21.6	0.29	2.18	66	1.36	90	6	0^+	0	
42	22.9	0.29	2.18	66	1.36	90	5	0^+	0	
43	55.9	0.22	2.18	64	1.34	86	8	0^+	0	
February 1975										
44	27.9	0.05	3.86	21	2.38	49	8	-3	-1	
45	50.8	0.05	2.57	48	1.61	78	8	-3	-1	
46	114.3	0.05	2.36	59	1.50	88	8	-3	-1	
47	121.9	0.04	2.36	59	1.50	88	8	-3	-1	
48	40.6	0.27	2.36	59	1.50	88	8	-3	-1	
49	96.5	0.07	2.36	59	1.50	88	8	0^+	0	Cuts made in lock wall ice collars
50	86.4	0.08	2.36	59	1.50	88	8	0^+	0	
51	55.9	0.04	2.36	59	1.50	88	81	0^+	0	
52	55.9	0.16	2.36	59	1.50	88	8	0^+	0	
53	35.6	0.16	2.36	59	1.50	88	56	0^+	0	
54	55.9	0.18	2.36	62	1.54	96	15	0^+	0	
55	41.9	0.24	2.36	62	1.54	96	15	0^+	0	

TABLE III

CUTTING SIMULATED SEA ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Remarks
January 1979 — Cuts made in floating ice sheet (Ref. 6)									
1	20.3	0.46	1.51	53	0.59	31	8	-22	46% "through"
2	12.2	0.51	1.51	47	0.55	26	8		
3	11.2	0.53	1.51	40	0.50	20	8		
4	8.1	0.55	1.51	33	0.46	15	8		Spalling with cut
5	6.9	0.51	1.51	27	0.42	11	8		Spalling with cut
6	4.1	0.51	1.51	20	0.36	7.5	8		Spalling with cut
7	2.8	0.51	1.51	13	0.29	3.7	8		Spalling only
8	11.9	0.99	1.51	53	0.59	31	8		4 mm kerf
9	8.9	1.06	1.51	47	0.55	26	8	-17	
10	6.4	0.75	1.51	40	0.50	20	8		
11	8.9	0.82	1.51	40	0.50	20	8	-16	
12	17.3	0.20	1.51	33	0.46	15	8		31% "through"
13	15.5	0.51	1.51	47	0.55	26	8		
14	10.2	0.55	1.51	40	0.50	20	8		Spalling with cut
15	23.4	0.33	1.51	53	0.59	31	8		100% "through"
16	23.4	0.35	1.51	47	0.55	26	8		100% "through"
17	16.0	0.38	1.51	40	0.50	20	8		
18	9.7	0.46	1.51	33	0.46	15	8		
19	24.1	0.22	1.51	53	0.59	31	8		100% "through"
20	24.1	0.35	1.51	47	0.55	26	8		100% "through"
21	24.8	0.35	1.51	40	0.50	20	8		100% "through"
22	11.7	0.33	1.51	33	0.46	15	8		

TABLE III (Cont'd)

CUTTING SIMULATED SEA ICE WITH "HIGH" PRESSURE WATER JETS

No.	Average Penetration Y(cm)	Average Traverse Speed u(km/h)	Nozzle Diameter d(mm)	Nozzle Pressure p(MPa)	Nozzle Flow Q(L/s)	Hydraulic Power HP(kW)	Average Nozzle Stand-off s(cm)	Ambient Temperature T_a(°C)	Remarks
January 1979 — Cuts made in floating ice sheet (Ref. 6) (Cont'd)									
23	24.8	0.15	1.51	33	0.46	15	8		100% "through"
24	9.4	0.51	1.51	33	0.46	15	8	-15	
25	17.5	0.29	1.51	33	0.46	15	8		
26	19.0	0.31	1.51	40	0.50	20	8		38% "through"
27	12.7	0.48	1.51	40	0.50	20	8		

FIG. 1: WATER JET CUTTING OF FLOATING ICE SHEET
(JET FROM 12.70 mm BORE NOZZLE)

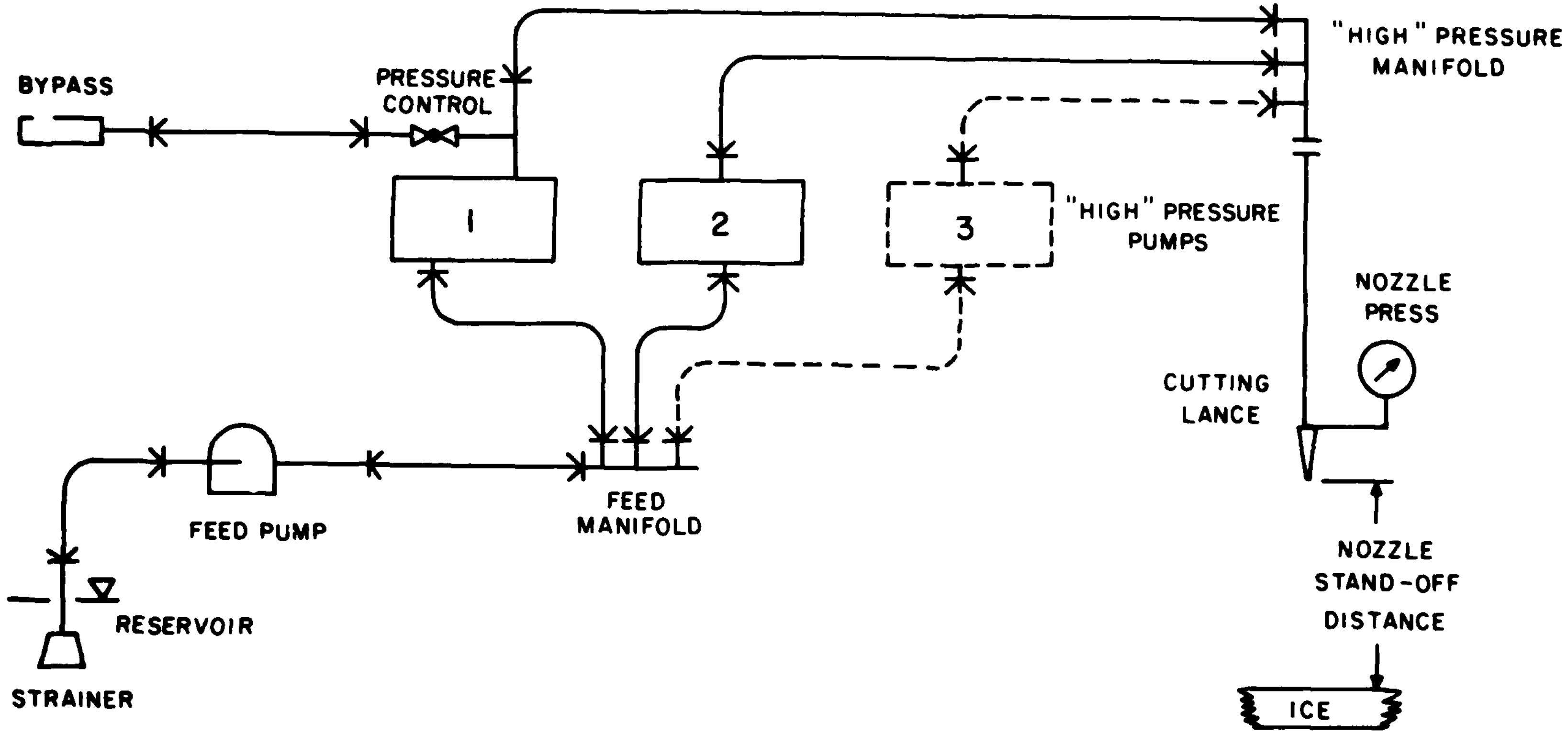

FIG. 2: WATER SYSTEM SCHEMATIC

FIG. 3: FIELD TESTING OF WATER JET CUTTING

FIG. 4: WATER JET CUTTING IN THE LABORATORY
(JET FROM 1.51 mm BORE NOZZLE)

FIG. 5: KERF CUT BY WATER JET

FIG. 6: SPALLED TRENCH CUT BY WATER JET

FIG. 7: CROSS-SECTION OF POND ICE

FIG. 8: BOTTOM PROFILE OF ICE SHOWING BOTTOM BROKEN-OUT
(SAW CUT THROUGH TO SHOW POSITION AND SIZE OF ORIGINAL WATER JET CUT)

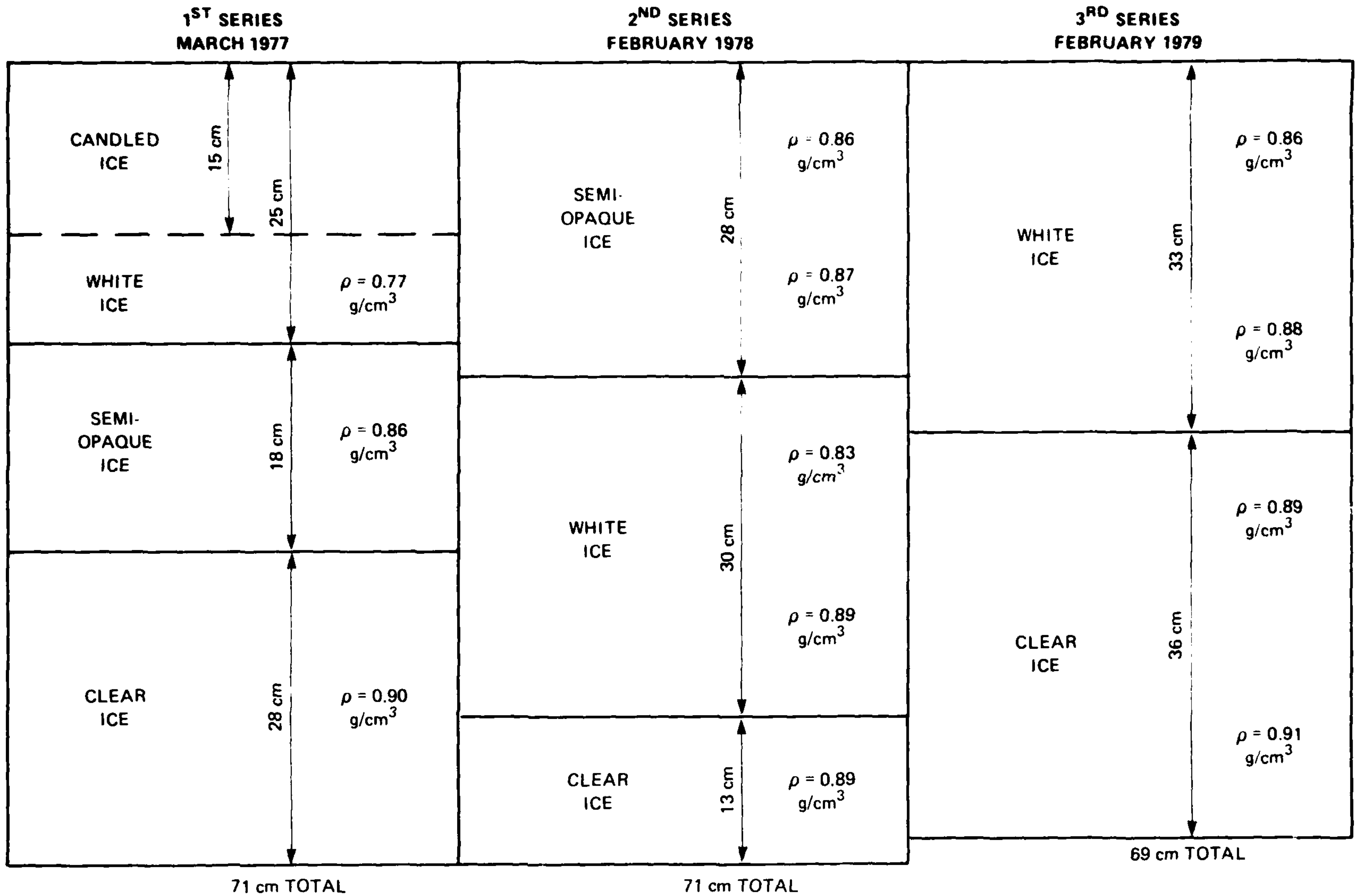

FIG. 9: ICE CHARACTERISTICS – FIELD TESTS

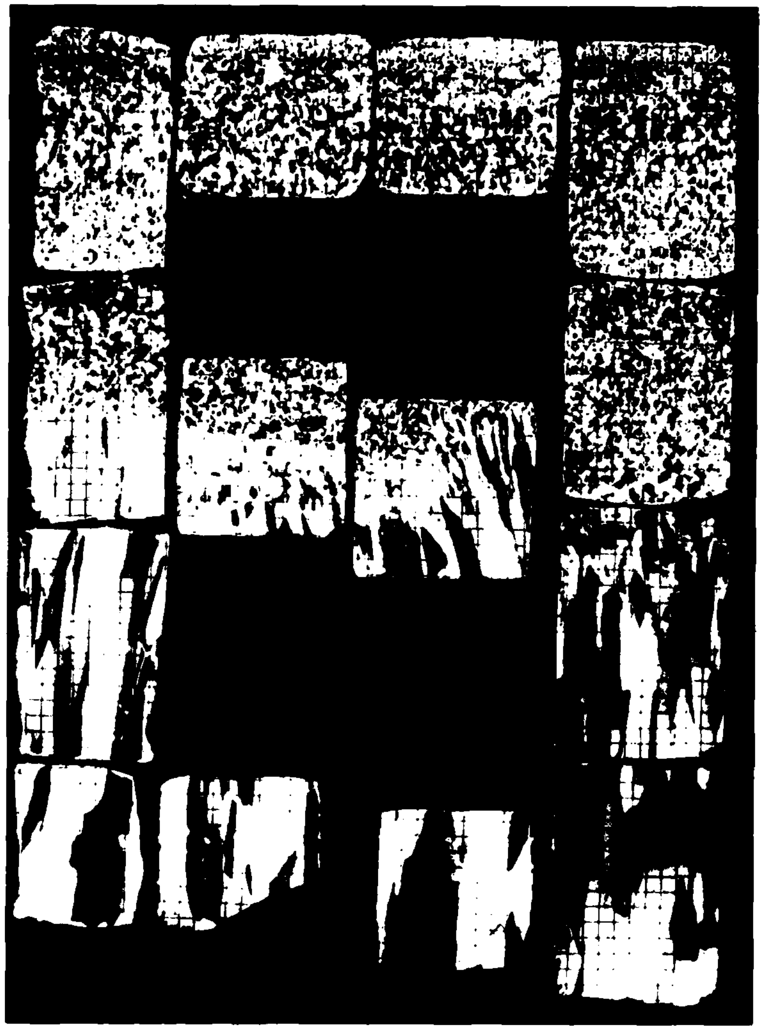

FIG. 10: MONTAGE OF THIN SECTIONS FROM THIRD SERIES OF FIELD TESTS – FEBRUARY 1979

FIG. 11: THIN SECTION OF LABORATORY FRESH WATER ICE SHEET

FIG. 12: VERTICAL THIN SECTION OF SIMULATED SEA ICE

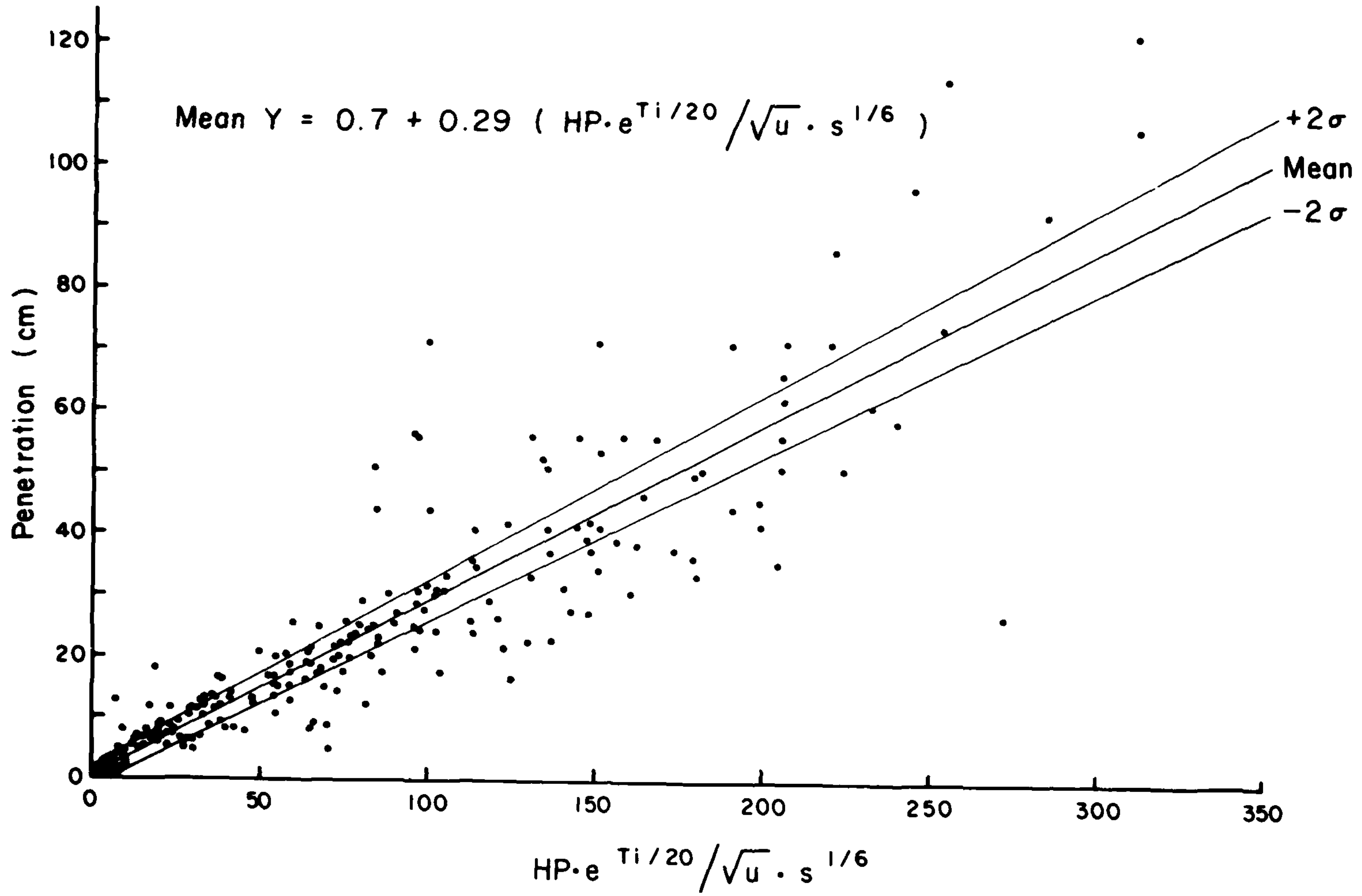

FIG. 13: CUTTING FRESH WATER ICE WITH WATER JETS

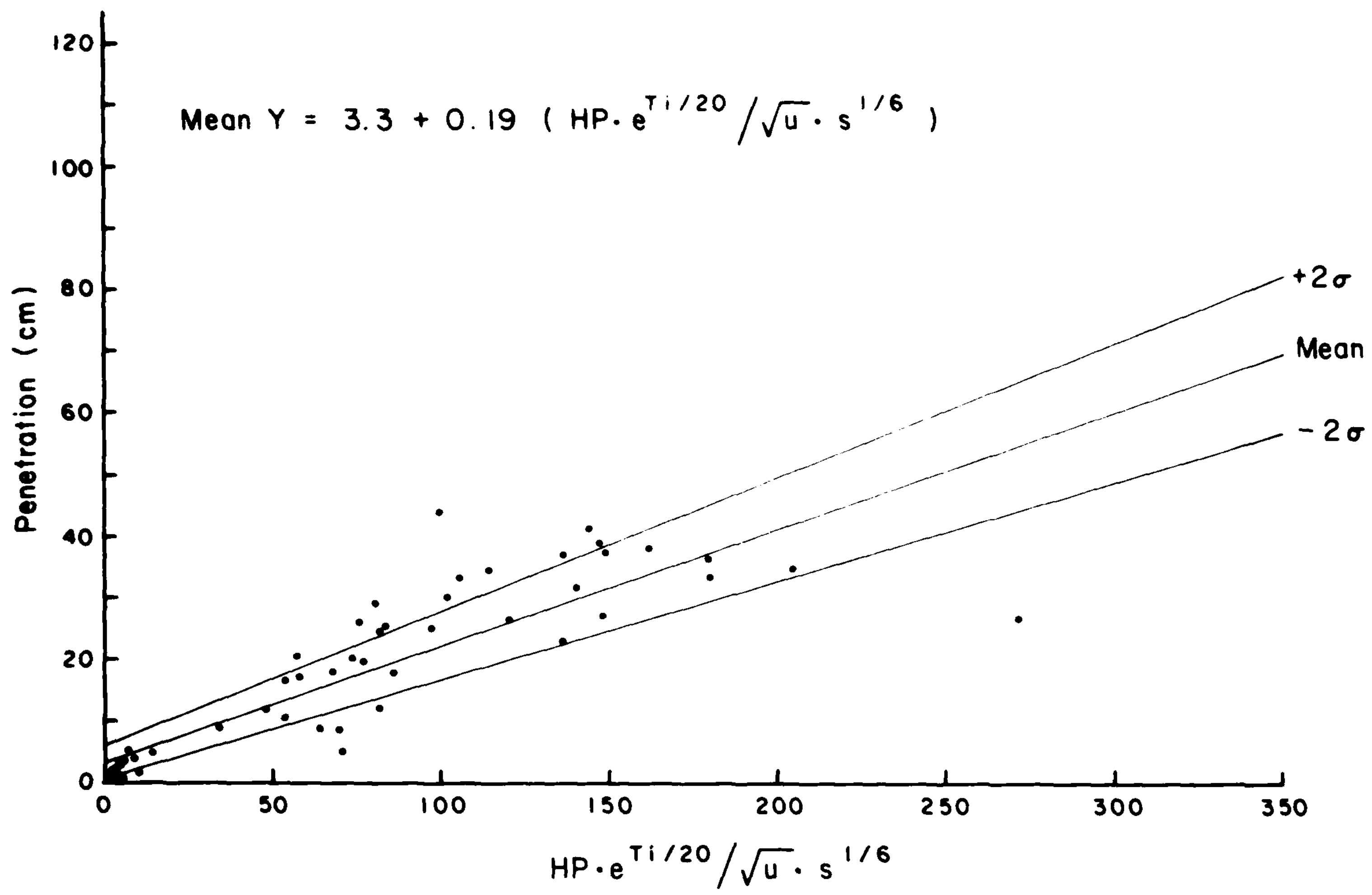

FIG. 14: SPALLING CUTS OF FRESH WATER ICE

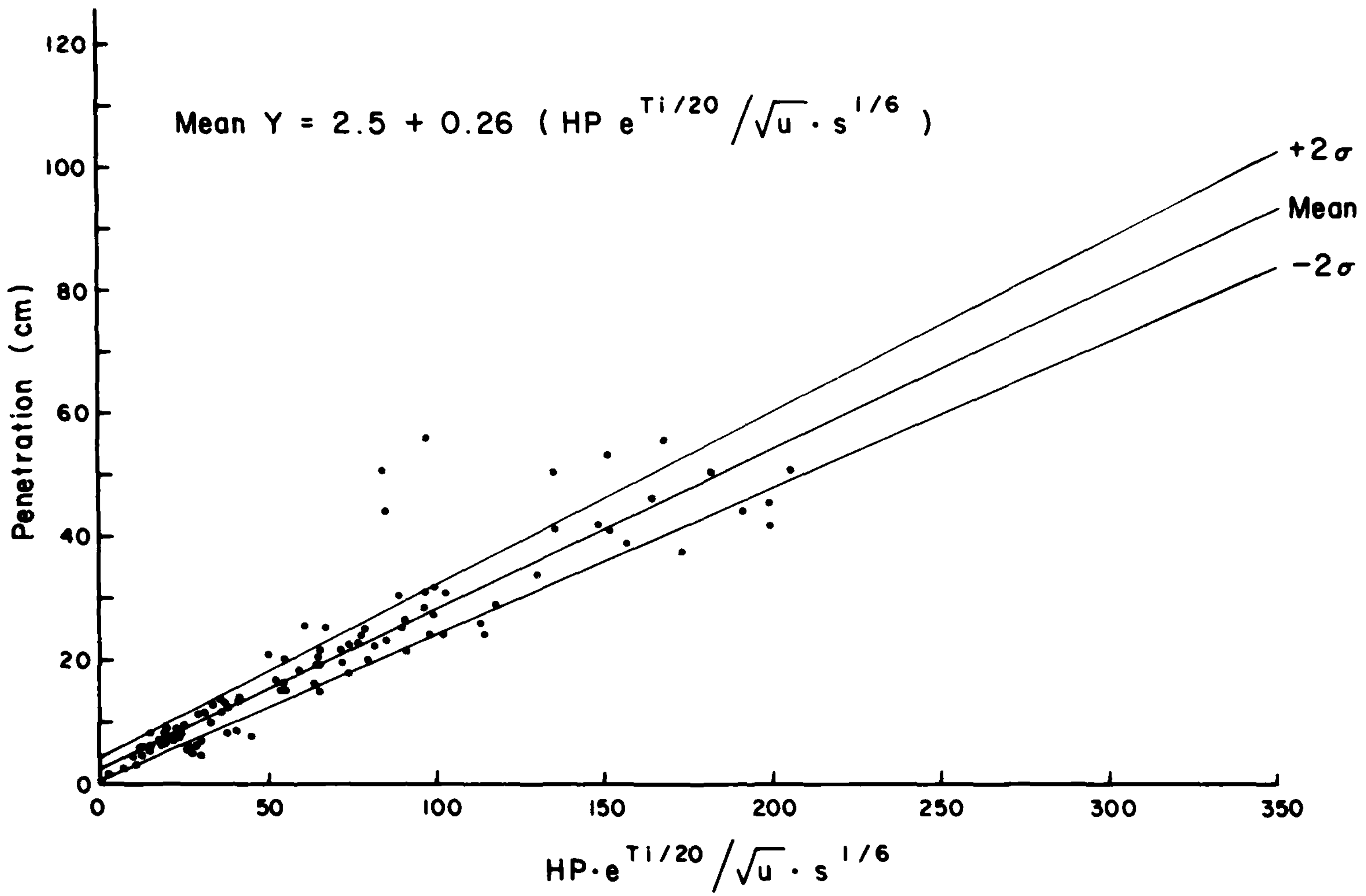

FIG. 15: KERFING CUTS OF FRESH WATER ICE

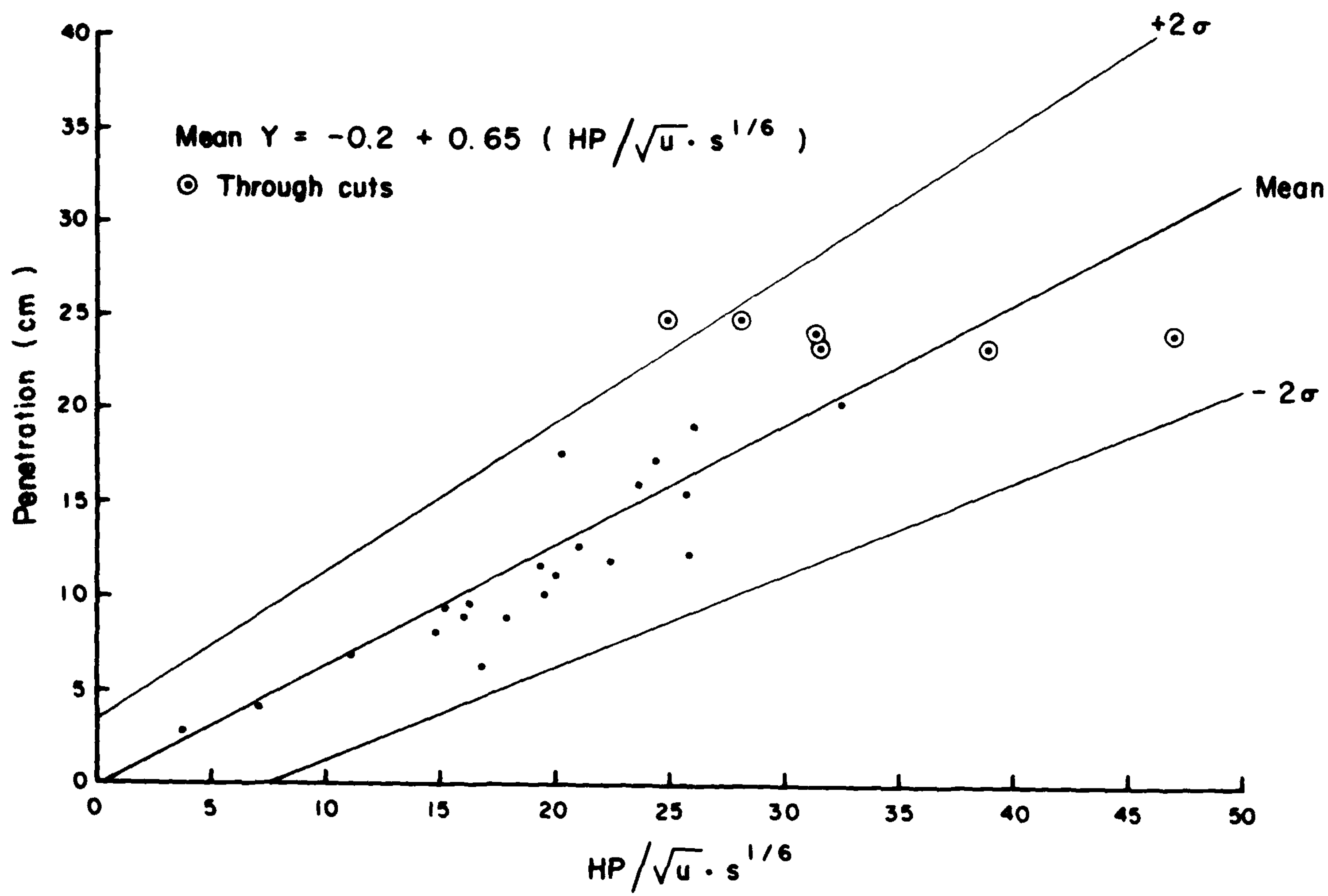

FIG. 16: CUTTING SIMULATED SEA ICE WITH WATER JETS

NRC DME MD-57 UNCLASSIFIED
National Research Council Canada. Division of Mechanical Engineering.

CUTTING ICE WITH HIGH PRESSURE WATER JETS
Coveney, D.B. July 1981. 48 pp. (incl. tables and figures).

1. Ice (Rivers, lakes, etc.)
2. Jet cutting

I. Coveney, D.B.
II. NRC DME MD-57

The potential of high pressure water jets to cut slots in an ice sheet, primarily for possible use as an assist to icebreaking, has been under investigation by the Division of Mechanical Engineering of the National Research Council of Canada.

In the field, slots have been cut into and through fresh water ice about 0.7 m thick with water jets applying up to about 260 kW of power to the ice. Each ice sheet consisted of a clear bottom layer and multiple upper layers of opaque white ice. The ice temperature just below the top surface ranged from −21°C to 0°C. In the laboratory, cuts to more than 17 cm were made in artificially grown, essentially clear fresh water ice and cuts to almost 25 cm were made in a simulated sea ice. Up to 30 kW was applied to the fresh water ice and up to 31 kW was applied to the simulated sea ice.

This report describes the ice cutting performance of small to moderate scale water jets. The majority of cuts produced a narrow, clear kerf indicative of erosion in a ductile material, while other cuts produced a wide spalled trench indicative of spalling in a brittle material. Still others produced a combination of the two modes of cutting with a wide shallow trench and a narrow deep kerf below the trench. In many cases the ice was also crazed extensively by the water jet. The causes and the effects of these characteristics on ice cutting performance are discussed along with the effects of jet traverse speed, nozzle diameter, nozzle pressure, nozzle stand-off, ice characteristics and the overall scale of the system. An empirical relationship derived by regression analysis is presented, correlating the jet penetration to the power in the jet, the jet traverse speed, the nozzle stand-off and the estimated ice temperature.

NRC No. 1964[illegible]

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The potential of high pressure water jets to cut slots in an ice sheet, primarily for possible use as an assist to icebreaking, has been under investigation by the Division of Mechanical Engineering of the National Research Council of Canada.

In the field, slots have been cut into and through fresh water ice about 0.7 m thick with water jets applying up to about 260 kW of power to the ice. Each ice sheet consisted of a clear bottom layer and multiple upper layers of opaque white ice. The ice temperature just below the top surface ranged from −21°C to 0°C. In the laboratory, cuts to more than 17 cm were made in artificially grown, essentially clear fresh water ice and cuts to almost 25 cm were made in a simulated sea ice. Up to 30 kW was applied to the fresh water ice and up to 31 kW was applied to the simulated sea ice.

This report describes the ice cutting performance of small to moderate scale water jets. The majority of cuts produced a narrow, clear kerf indicative of erosion in a ductile material, while other cuts produced a wide spalled trench indicative of spalling in a brittle material. Still others produced a combination of the two modes of cutting with a wide shallow trench and a narrow deep kerf below the trench. In many cases the ice was also crazed extensively by the water jet. The causes and the effects of these characteristics on ice cutting performance are discussed along with the effects of jet traverse speed, nozzle diameter, nozzle pressure, nozzle stand-off, ice characteristics and the overall scale of the system. An empirical relationship derived by regression analysis is presented, correlating the jet penetration to the power in the jet, the jet traverse speed, the nozzle stand-off and the estimated ice temperature.

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